Limits on the effective quark radius from inclusive ep scattering at HERA

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On behalf of ZEUS Collaboration

- Combined inclusive DIS data from HERA
- Quark form-factor model
- Beyond-the-Standard-Model analysis combined with PDFs fit
HERA - world’s only $e^\pm p$ collider

HERA operated during 1992 - 2007 with:

- $e^\pm$ energy of 27.5 GeV;
- $p$ energies of 920, 820, 575 and 460 GeV.

**H1** and **ZEUS** - two general purpose collider experiments at HERA:

- $\sim 0.5 \text{ fb}^{-1}$ of luminosity were recorded by each experiment.

Kinematics of the $e^\pm p$ collisions:

$$Q^2 = - (k - k')^2$$

$$xBj = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$
HERA inclusive data combination

• 2927 data point combined to 1307

• up to 8 data points combined to 1

• impressive improvement of precision due to:
  - increased statistics
  - better understanding of systematics
  - cross-calibration of the data from two experiments

QCD analysis of the combined DIS data

Neutral Current:

\[
\frac{d^2 \sigma_{NC}^{e^+p}}{dx dQ^2} = \frac{2\pi \alpha^2}{xQ^4} \cdot (Y_+ \cdot F_2 \pm y^2 \cdot y^2 \cdot F_L)
\]

\[
F_L \sim \alpha_s g
\]

Charged Current:

\[
\frac{d^2 \sigma_{CC}^{e^+p}}{dx dQ^2} = \frac{G_F^2}{4\pi x} \cdot \kappa^2 \cdot (Y_+ \cdot W_2^\mp \pm xW_3^\mp - y^2 \cdot W_L^\mp)
\]

\[
\kappa = \frac{M_W^2}{M_W^2 + Q^2}
\]

At the Quark-Parton Model:

\[
F_2 = \frac{4}{9} (xU + x\bar{U}) + \frac{1}{9} (xD + x\bar{D})
\]

\[
xF_3 \sim xu + xd
\]

Parton Density Functions parametrisation at the starting scale \(Q^2_0 = 1.9 \text{ GeV}^2\):

\[
xg(x) = A_g x B_g (1 - x)^C_g - A'_g x B'_g (1 - x)^C'_g
\]

\[
xu(x) = A_u x B_u (1 - x)^C_u (1 + E_u x^2)
\]

\[
xd(x) = A_d x B_d (1 - x)^C_d
\]

\[
x\bar{U}(x) = A_{\bar{U}} x B_{\bar{U}} (1 - x)^C_{\bar{U}} (1 + D_{\bar{U}} x)
\]

\[
x\bar{D}(x) = A_{\bar{D}} x B_{\bar{D}} (1 - x)^C_{\bar{D}}
\]

- fixed or calculated by the sum-rules
- set equal

Evolve to any \(Q^2 > Q^2_0\) with DGLAP at NLO.

Obtained PDFs are referred to as ZCIPDFs and have a good agreement with the HERAPDF 2.0.

How big is a quark?

One of the possible parameterisations of the deviations from the Standard Model - spatial distribution or substructure of electrons and/or quarks.

In a semi-classical form-factor approach cross sections are expected to decrease at high-$Q^2$:

\[
\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot \left(1 - \frac{R_e^2}{6} Q^2\right)^2 \cdot \left(1 - \frac{R_q^2}{6} Q^2\right)^2
\]

There $R_e^2$ and $R_q^2$ are the mean-square radii of the electron and quark, respectively.

Same dependence expected for NC and CC $e^+p$ and $e^-p$.

Electrons were assumed to be point-like, $R_e^2 = 0$, and both, positive and negative values of $R_q^2$ were considered.
Reason for the simultaneous fit procedure

➤ BSM signal in the data could affect the PDF fit and result in biased PDFs.

➤ Use of the biased PDFs in the BSM analysis would result in overestimated limits.

➤ This cannot be avoided for the analysis of HERA data by using another available PDF set, since all high-precision PDF fits include the DIS data from HERA (MMHT2014, NNPDF 3.0, etc.).

➤ The proper procedure for a BSM analysis of the HERA data - global QCD analysis which includes a possible contribution from BSM processes.
Necessity of the simultaneous fit procedure

Pseudodata generated for values of $R^2_q = R^2_q^{\text{True}}$

- $R^2_q + \text{PDF fit}$
- $R^2_q$-only fit after SM PDF fit

Pseudodata generated for value of $R^2_q = 0$

- $R^2_q + \text{PDF } \chi^2 \text{ scan}$
- $R^2_q$-only $\chi^2 \text{ scan}$

$R^2_q + \text{PDF} \text{ procedure provides unbiased results of } R^2_q^{\text{Fit}}$

$R^2_q$-only procedure results in too strong limits
## Limits setting method

Limits are derived in a frequentist approach using the technique of Monte Carlo replicas. Two procedures were used:

<table>
<thead>
<tr>
<th><strong>R_q-only</strong></th>
<th>Monte Carlo replicas generated for $R_{q}^{\text{true}}$ using ZCIPDFs and $R_{q}^{\text{fit}}$ parameter fitted with PDFs <strong>fixed to ZCIPDFs</strong>.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PDF + R_q</strong></td>
<td>Monte Carlo replicas generated for $R_{q}^{\text{true}}$ using ZCIPDFs and $R_{q}^{\text{fit}}$ parameter fitted <strong>simultaneously</strong> with PDFs.</td>
</tr>
</tbody>
</table>

The **PDF + R_q** frequentist method was the main analysis method.
Monte Carlo replicas

Monte Carlo replicas of the cross-section measurements were calculated with:

\[
\mu^i = \left[ m^i_0 + \sqrt{\delta^2_{i,\text{stat}} + \delta^2_{i,\text{uncor}}} \cdot \mu^i_0 \cdot r_i \right] \cdot \left( 1 + \sum_j \gamma^i_j \cdot r_j \right)
\]

Cross-section prediction from the ZCIPDF modified with \( R^2_q^{\text{True}} \)

Measured cross-section value

Correlated systematic uncertainties

Relative statistical and uncorrelated systematic uncertainties

Random numbers from a normal distribution

Fitted MC replicas for \( R^2_q^{\text{True}} = 0.48 \cdot 10^{-16} \text{ cm} \):

- **R_q-only**
  - \( (R^2_q)^{\text{Frac}} = -0.3544 \times 10^6 \text{ GeV}^{-2} \)
  - \( (R^2_q)^{\text{True}} = 6 \times 10^6 \text{ GeV}^{-2} \)
  - Fraction of \( (R^2_q)^{\text{Frac}} < (R^2_q)^{\text{Frac}} < (R^2_q)^{\text{Frac}} < (R^2_q)^{\text{Frac}} \): 0.96 %

- **PDF + R_q**
  - \( (R^2_q)^{\text{Frac}} = -0.4786 \times 10^6 \text{ GeV}^{-2} \)
  - \( (R^2_q)^{\text{True}} = 6 \times 10^6 \text{ GeV}^{-2} \)
  - Fraction of \( (R^2_q)^{\text{Frac}} < (R^2_q)^{\text{Frac}} < (R^2_q)^{\text{Frac}} < (R^2_q)^{\text{Frac}} \): 1.84 %
R_q limits with the MC replicas

**R_q-only**

ZEUS

Probabilities close to 5% fitted with:

\[ f(x) = 5 \cdot e^{(x-A) \cdot B} \]

\[-[0.42 \cdot 10^{-16} \text{ cm}]^2 \leq R_q^2 \leq [0.40 \cdot 10^{-16} \text{ cm}]^2\]
**R_q limits with the MC replicas**

**PDF + R_q**

*ZEUSS*

- **Probabilities close to 5% fitted with:**
  \[ f(x) = 5 \cdot e^{(x-A) \cdot B} \]

- **PDF + R_q replicas**
- **PDF + R_q fit**
- **R_q-only replicas**
- **R_q-only fit**
- **95% C.L. limit**

**Entries**

- **PDF + R_q**
  \[
  \begin{align*}
  \langle R^2 \rangle^{\text{fit}} &= 6.0786 \times 10^{-16} \text{ GeV}^2 \\
  \langle R^2 \rangle^{\text{true}} &= 6.0786 \times 10^{-16} \text{ GeV}^2 \\
  \text{Fraction of } \langle R^2 \rangle^{\text{true}} < \langle R^2 \rangle^{\text{fit}}: &\quad 1.84 \%
  \end{align*}
  \]

Comparison to Data

Neutral Current:

\[
\frac{\sigma}{\sigma_{\text{SM}}} \rightarrow \left( 1 \right)_{\text{SM}} \rightarrow \text{ZCIPDF total unc.}
\]

Quark Radius

95\% CL Limits

- \( R_q^2 = (0.43 \times 10^{-16} \text{cm})^2 \)
- \( R_q^2 = -(0.47 \times 10^{-16} \text{cm})^2 \)

Charged Current:

\[
\frac{\sigma}{\sigma_{\text{SM}}} \rightarrow \left( 1 \right)_{\text{SM}} \rightarrow \text{ZCIPDF total unc.}
\]

Quark Radius

95\% CL Limits

- \( R_q^2 = (0.43 \times 10^{-16} \text{cm})^2 \)
- \( R_q^2 = -(0.47 \times 10^{-16} \text{cm})^2 \)

Summary

► Combined HERA inclusive DIS cross-section measurements allow to study the proton substructure at the scales down to $10^{-17}$ cm.

► The simultaneous analysis of PDFs and quark form factor yield the 95% C.L. limits of the effective quark radius of

$$-[0.47 \cdot 10^{\text{-16}} \text{ cm}]^2 \leq R_q^2 \leq [0.43 \cdot 10^{\text{-16}} \text{ cm}]^2$$

► The simultaneous analysis is necessary since the limits that would be obtained otherwise are too strong by about 10%.

More results of the combined PDFs and BSM analysis were presented by K. Wichmann today at 9:45.